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SUPPLEMENT
to
THE SYNOPTIC STRATOSPHERE

U. S. NAVY WEATHER RESEARCH FACILITY
NORFOLK, VIRGINIA

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Supplement

to

THE SYNOPTIC STRATOSPHERE
(NWRF 26-0359-023)

APPLIED RESEARCH
A-R-O-W-A
OPERATIONAL WEATHER ANALYSIS

U. S. NAVY WEATHER RESEARCH FACILITY
BUILDING R-48
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FOREWORD

Task 26, "High Tropospheric and Stratospheric Analysis and Forecasting," was assigned to the U. S. Navy Weather Research Facility for the purpose of developing improved upper atmospheric analysis and forecasting techniques and establishing models for the upper atmosphere. As a part of the work on Task 26, NWRF published, in March 1959, a nonmathematical survey of what was then known about the stratospheric regions, from the tropopause to 100,000 feet ("The Synoptic Stratosphere," NWRF 26-0359-023).

In the short time since publication of "The Synoptic Stratosphere", much data collected during the International Geophysical Year have become available, and many new studies have greatly increased our understanding of the stratosphere. To summarize the recent advances in this rapidly expanding field of knowledge, Dr. H. A. Panofsky (scientific consultant to NWRF and author of the original publication) has written this supplement to "The Synoptic Stratosphere".

Special thanks are due to Mr. Sidney Teweles of the U. S. Weather Bureau, who critically read this supplement and made useful suggestions.

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Introduction

Since the original publication of The Synoptic Stratosphere our knowledge of the lower and middle stratosphere has increased considerably, largely through the IGY effort. Some stratospheric charts constructed from IGY data have already appeared: with NWRF sponsorship, the U.S. Weather Bureau (1959) has published a series of 10 mb. charts for every 10 days from July 5, 1957 through June 25, 1958, covering North America and much of the Atlantic and Pacific Oceans. Also, Scherhag and his group in Berlin have published daily hemispheric charts at 50 mb., 25 mb., and 10 mb. for the first quarter of 1958 (Behr, et.al., 1960 a, b, c). We have thus gained important new insights into the rapid warming process at the end of the winter regime. This has been supplemented by the 25 mb. charts constructed by Hare (1960) which cover the 1959 warmings.

Annual Variation of Circulation and Temperature

The middle stratosphere, for which the 25 mb. level can be regarded as typical, is covered in the winter by a cold low, centered near the pole, with west winds extending to latitude 20° in the western Atlantic and 35° in the Pacific. Warm highs are located at these latitudes. The central temperature of the low reaches below -80°C. In summer, on the other hand, the hemisphere is covered by a somewhat less intense warm high, with easterlies everywhere. The central temperatures are about -35°C. The recent publications have shown just how the tremendous seasonal changes occur throughout the year.

First, some general remarks: at 10 mb. and 25 mb., highs are always warm and lows cold, although one side of a system may be somewhat warmer than the other. Also, the systems are generally devoid of small-scale structure, there usually just being two or three lows north of the middle latitudes. These systems seem to be purely stratospheric -- there seems to be no connection between them and tropospheric cyclones. In this, the 10 mb. surface differs from the 100 mb. surface where tropospheric patterns, somewhat smoothed, are still clearly discernible. After the large warm high has persisted without disturbance through the period from the beginning of June to the middle of August, a cold low develops near the pole about the last half of August. This low, with temperatures in its center initially about -45°C., dominates the scene from that time on until the "sudden warming" the following year. The central temperature falls at an average rate of 1/3°C.

per day until the end of November, by which time the winter regime is fully established with the temperatures near the center of the polar low about -80°C. While the low deepens, a high pressure belt gradually moves southward. By September 15, it is at latitude 45° N., by October 15 at latitude 30° N. At the end of October the belt has reached its normal wintertime position. In November the belt of highs tends to break down into several centers, which may account for the fact that debris from the exploding Krakatao (near the equator at 10 mb.) spreads into middle latitudes in November.

The rate of cooling characteristic of this cyclogenesis is just what would be expected on the basis of radiational processes alone. However, it is dangerous to generalize; whereas the cooling process and establishment of the winter regime was smooth in late 1957, it was interrupted in late 1958. The character of this interruption (as well as of later interruptions in the winter) is this: at the outskirts of the cold cyclone are located large warm anticyclones. In the Pacific, these anticyclones often come quite far north and produce a ridge, often in Alaska. Occasionally, either the Pacific anticyclone or else a similar one in the eastern Atlantic may gain in intensity and invade Canada. This happened, in particular, during November and the beginning of December 1958. Such a process, of course, disrupts the "normal" cooling and postpones it somewhat. Figure 1 (from Hare, 1960) shows this disturbed autumnal cooling pattern. As a result of the "warm phase" of fall 1958, the complete winter regime was established only in the middle of December.

The change from the winter to the summer regime usually proceeds in two distinct parts in the Northern Hemisphere: First comes the period of impulsive warmings which greatly weakens the cold cyclone, but does not destroy it; marked examples of this phase usually occur in January, February, or March. The second part is the establishment of the easterlies which is not complete until the beginning of June and starts about the beginning of May. In the Southern Hemisphere the first phase seems to be missing.

Let us start with a typical winter cyclone centered near the pole (fig. 2). One or another of the highs on the periphery of the cyclone intensifies, and the temperature in regions influenced by this impulsive anticyclogenesis may become warmer than -20°C. In particular, in 1958, both the Pacific and the Atlantic highs intensified throughout January. By January 25, warm highs had invaded the Mediterranean and

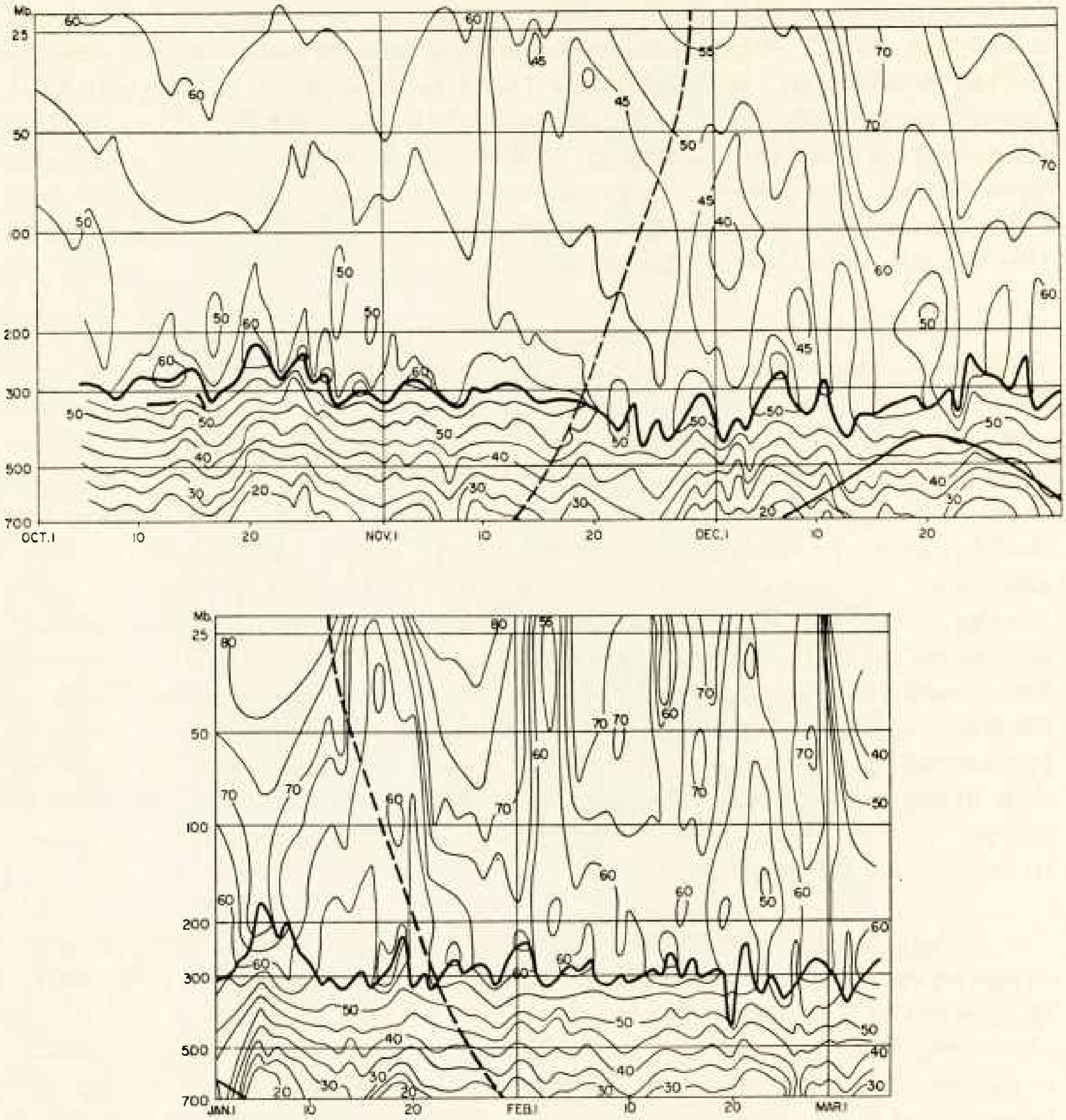

Figure 1. Time-height section of temperature (deg Celsius) at Resolute (924), 6 October-5 March, 1958-59 winter, from 700 to 25 mb. Dashed curve is limit of polar night (sun below horizon). Solid line is civil twilight (solar elevation: -6 deg with respect to the apparent horizon). Heavy black line is arctic tropopause. Note that the impulsive temperature changes are of either sign [7].

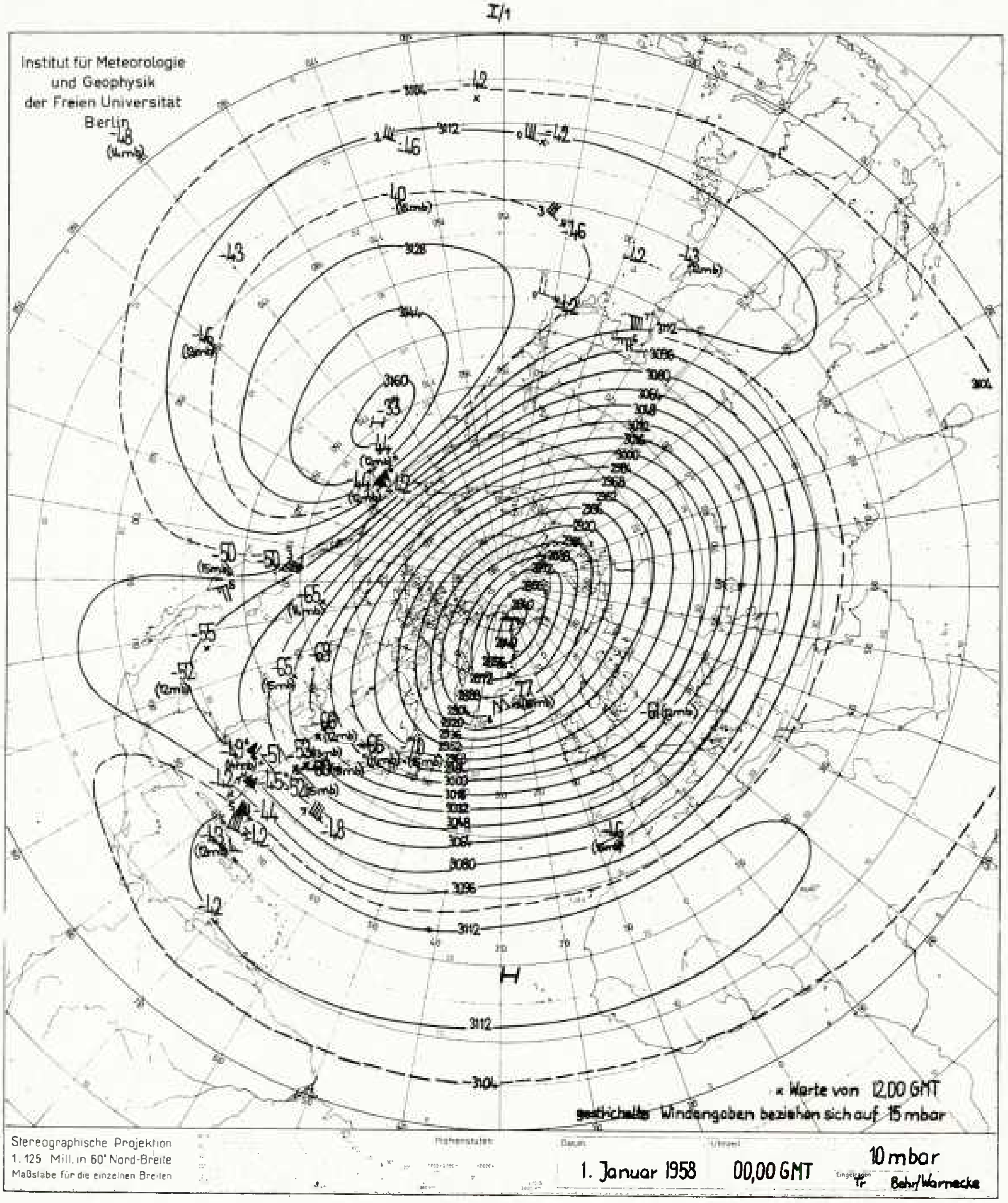

Figure 2. 10-mb analysis, 0000 GMT 1 January 1958. Solid lines are contour heights in tens of meters, dashed lines are isotherms in degrees Centigrade [3].

Alaska. By January 30, these highs dominated the North Atlantic and western Canada; the lows were split in two, with the major low over Siberia, and only a small remnant in eastern Canada. By February 1, the Atlantic high further retrograded toward the high in western Canada, leaving only a trough with no closed contours in eastern Canada. Only the Siberian low remained. At this time the temperatures in northern Canada had risen to the minus thirties. From then on throughout the first 20 days or so of February the high dominated North America, whereas the strong low in Eurasia gradually weakened. Finally, by the end of February, the low, still weak, spread across the pole and the polar vortex was reestablished in more or less its original position. Eventually, the low strengthened again, but never reached the intensity of the polar vortex prior to the warm invasion. This can be seen by comparing figure 3, after the warming, with figure 2 (figs. 2 and 3 from Scherhag's maps, January vs. end of March).

The invasions of the highs just described are different in every year. In some years, such as in 1959, warm air invaded Canada rapidly both at the beginning of February, and of March. Even before those "explosive" or "impulsive" warmings, minor warmings occurred throughout December and January with cooling in between. Usually the last warming is the most impressive.

Although the warming process has been associated with the motions of the warm highs, it cannot be an entirely advective process. The isotherms generally move more slowly than the air, and the temperatures during a warming episode are much warmer than they had been anywhere before; thus, subsidence must play an important role. In fact, the vertical velocities have recently been estimated to be at least 5 cm./sec. in limited regions. Some confirmation of these large vertical motions comes from the observations of ozone and atomic debris, which will be discussed in the next section.

Some recent rocket observations have shown that the "explosive" warming is even faster at higher levels and occurs earlier. Two ascents at Fort Churchill on Hudson Bay 4 days apart showed a warming at 50 km. of 70°C.

Consider now the situation at the end of March, when a weak polar vortex at 10 mb. and 25 mb. has been reestablished, after several interludes of invasion of warm air. How does this westerly regime change to easterlies? The first indication of the monsoonal change occurs at

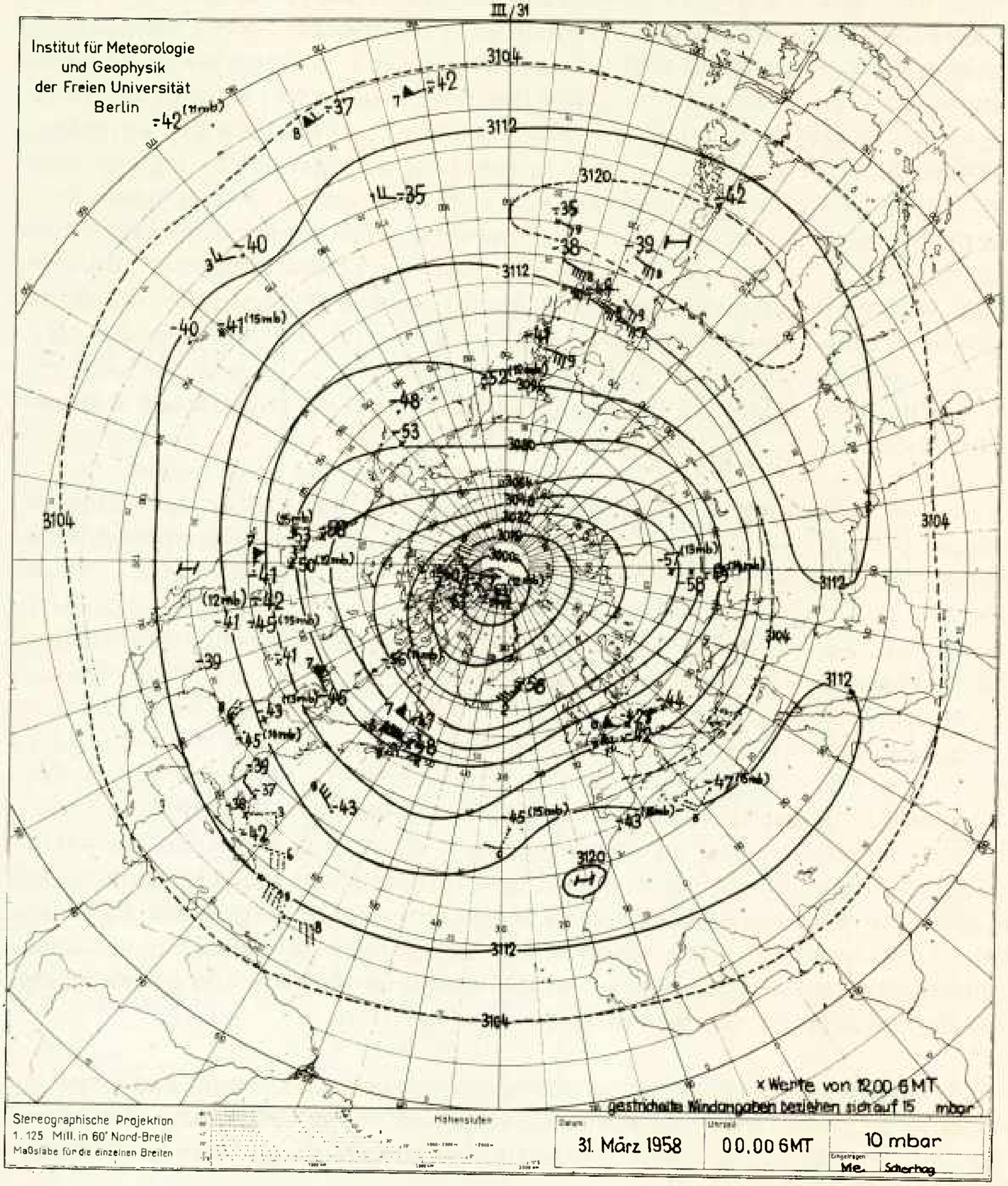

Figure 3. 10-mb analysis, 0000 GMT 31 March 1958. Solid lines are contour heights in tens of meters, dashed lines are isotherms in degrees Centigrade [3].

the beginning of May, when a small warm high appears near the pole. This high gradually grows. By the middle of May, the lows have been squeezed into a belt around latitude 50° N., between the belt of subtropical highs and the polar belt. At the same time, the temperature of the polar high has climbed into the minus thirties. This rise of temperature is probably faster than that which could be expected to result from radiation -- and subsidence, this time less pronounced, must be present. By the beginning of June, the low contour belt has been completely squeezed out and the whole hemisphere is dominated by easterlies. At the same time, the temperature field at 10 mb. is almost completely flat, with temperatures in the minus thirties at the pole and the minus forties in the Tropics.

In the Antarctic, the change from winter circulation to summer circulation seems to be different. The cold polar vortex remains until after the sun comes back, and pronounced warming does not set in until November. There is no invasion by warm highs earlier, perhaps because the topography is more symmetrical and there is nothing in the Southern Hemisphere corresponding to the Alaskan ridge.

When the warming finally does occur, however, it is again faster than that which could be accounted for by radiation, and is also faster than the autumnal cooling. Again, advection and subsidence must be important.

The Meridional Circulation

So far, the discussion has been almost entirely about the zonal portion of the circulation. Of course, at certain longitudes there are strong, meridional components; for example, in northwestern Canada the prevailing wind direction in the winter is from the northwest, due to the persistent Alaskan ridge.

However, the mean north-south circulation, averaged over all longitudes, cannot be measured directly, but some of its properties can be inferred from the behavior of water vapor, ozone, and radioactive elements.

The main feature of the water vapor distribution is that the relative humidity in middle latitudes decreases rapidly above the tropopause. This suggests that the air in the stratosphere has come from the Tropics near the tropopause where the low temperatures (-70°C.

and less) have removed most of the water vapor.

Radioactive debris has been put into the stratosphere at various times. Some of the most powerful explosions have occurred in the Tropics; nevertheless, most of the fall-out has occurred in middle and high latitudes. Incidentally, the fall-out reaches a maximum in the spring, a fact which also may be connected with the stratospheric circulation.

Finally, the total ozone amount in a vertical column is greatest near latitude 60°, and again shows a strong spring maximum. This is in spite of the theoretical result that most of the ozone is produced in the tropical stratosphere. As a matter of fact, in the middle stratosphere the ozone concentration decreases slowly toward the pole, so that a large amount of ozone at latitude 60° must be located in the troposphere and lower stratosphere.

All of these observations suggest a circulation from the Tropics toward the pole in the stratosphere. This may be an actual organized northward air motion, as suggested by Brewer (1949) and Dobson (1957). Or it may be an eddy exchange. That is, for example, air filled with radioactive debris may drift northward while pure air drifts southward; or air rich in ozone moves toward the pole, and air poor in ozone moves toward the Equator.

The same observations can be used to draw some conclusions about the vertical portion of the general circulation of the stratosphere. If a large amount of air is actually moving poleward, this suggests that air is moving upward through the equatorial tropopause and downward in middle or high latitudes. This hypothesis is confirmed by the excellent correlation between ozone amount and temperature, particularly during periods of rapid warming. At those times, Godson has shown that at Canadian stations, the total ozone in vertical columns increased rapidly, and the same situation occurred over Berlin during the sudden warming there in 1958.

The mechanism of this ozone increase is this: rapid warming implies subsidence. Subsidence brings ozone to lower levels. This disturbs the equilibrium of ozone above 25 mb., where new ozone is formed rapidly. At low levels, the equilibrium is also disturbed in that there is now too much ozone; but Craig (1950) and others have shown that ozone is so slowly destroyed at low levels that the ozone concen-

tration can be considered as a conservative property there. Therefore, subsidence means increase of total ozone.

Since rapid warming and subsidence occur in January or February, maximum ozone at high latitudes also would occur in the same months. Further south the maximum occurs a little later, because it takes time to transport the ozone southward.

Just as the late-winter subsidence is important in increasing the ozone concentration, it also brings radioactive strontium from the high stratosphere to the low stratosphere, where it can be mixed more easily with tropospheric air and eventually washed out. For, normally, there is very little vertical mixing in the stratosphere, and the residence time of radioactive debris in the stratosphere may be several years. Thus, the subsidence associated with the warming may also be responsible for the spring maximum of fall-out.

In summary, then, we have the following picture: air is rising through the cold tropical tropopause, is transported poleward in the stratosphere, and is moved downward periodically during the periods of the warming in arctic latitudes.

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